Evaluation of Correction Factors Applied in Photon Calibration of NIS TE Neutron Ionization Chambers

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Abstract: Calibrations of two tissue equivalent (TE) ionization chamber were made in five photon beams (100 kV, 180 kV, 250 kV, ^{137}Cs and ^{60}Co) with two different pure gases namely acetylene C_2 H_2 and carbon dioxide CO_2. The different calibration factors were compared both for in-air and in-water phantom, the measurements were performed according to the international atomic energy agency (IAEA) recommendations. For ionization chamber the total absorbed dose can be derived from the charge produced within its cavity employing a number of physical parameters. To discuss the charge produced in the cavity several correction factors which are related to the operational characteristics of the chambers have to be introduced. Information on the operational characteristics of two TE neutron ionization chambers were studied as a function of the effects of the warm-up to 3 hours, polarity, stem scattering, ion recombination, leakage current. Six different caps 1, 2, 3, 4, 6 and 8 mm were used to investigate wall thickness effect. Also, gas flow rate up to 31 ml/min and the radial & axial uniformity were investigated.

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1. Introduction:

The increase in the number of centers throughout the world which are using fast neutrons for radiotherapy has led to a need for accurate neutron dosimetry methods which will give comparable results in each of these centers. [Williams and Greening, 1980, Ruedi Risler and Alina Popescu 2010].

The use of calibrated tissue-equivalent (TE) ionization chambers is commonly considered to be the most practical method for total absorbed dose determinations in mixed neutron-photon fields for biomedical applications. [Zoetelief and Broerse, 1983]. Most ionization chambers are usually not employed as absolute instruments due to uncertainties in determining effective cavity volume, and hence the mass of gas therein, and due to uncertainties in the absolute value of *W*, the average energy required to produce an ion pair in the gas or gas mixture [Pszona, S. 2010].

The use of calibrated A-150 plastic TE ionization chamber with TE gas filling is recommended as the practical method of obtaining the tissue kerma in air and the absorbed dose in a TE phantom. This recommendation is based on the fact that TE chambers have been used as the principal dose measuring instrument by the neutron therapy groups in Europe, USA and Japan which are regularly treating patients. IAEA, (1984) and generally accepted as probably the most accurate method for measuring absorbed dose and kerma in most practical situations [Lindborg and Nikjoo 2011].

Although the hydrogen and nitrogen components in the chamber materials can be made to simulate that in tissue, for certain determinations, such as that of kerma in free air, it may be necessary to take into account the disturbance of the neutron fluence produced by the chamber itself. [Podgorsak, 2005].

According to Bragg-Gray principle, chamber homogeneity is achieved for neutron dosimetry using wall, gas, and insulator materials that have the same energy transfer coefficient for the primary radiation and the same stopping power for the secondary particles. Since the principal concern of this work is measurement of neutron absorbed dose in tissue, the ideal material for a homogeneous chamber is one which has an atomic composition similar to that of tissue. Such materials may be called tissue substitutes. [ICRU, 1989, Ferreira et al., 2010].

The absorbed dose, *Dg*, in the gas cavity of an ionization chamber is given by:

$$D_g = Q\frac{W}{e}\frac{1}{m} \qquad (1)$$

Where *Q* is the total charge produced within the cavity, *W* is the average energy required producing an ion pair in the gas, *e* is the charge of the electron and *m* is the mass of gas within the cavity.

In the SI-system D_g is expressed in Gy, Q and e in C, W in J and m in kg. Absorbed dose in the wall material adjacent to the cavity of the chamber, D_{m^*}, can be calculated from the energy absorbed by the gas using the gas-to-wall absorbed-dose conversion factor, $r_{m,g}$, similar to r introduced by Bichsel and Rubach (1978).

$$D_{m^*} = r_{m,g} D_g \quad (2)$$

For a cavity whose size is not negligible in relation to the range of the secondary charged particles generated in the wall, it is necessary to make more detailed calculations for the values of r as a function of cavity-size and neutron energy.

If the chamber wall is replaced by reference tissue, the absorbed dose in the tissue adjacent to the cavity of the chamber, D_{t^*}, is calculated from D_{m^*} using the ratio of mass energy absorption coefficients, $(\mu_{en}/\rho)_t / (\mu_{en}/\rho)_m$, in the tissue and wall material, assuming that there is charged particle equilibrium [Juan G. Miranda et al., 2004]:

$$D_{t^*} = \frac{(\mu_{en}/\rho)_t}{(\mu_{en}/\rho)_m} D_{m^*} \quad (3)$$

i.e. $$D_{t^*} = \frac{Q}{m}\frac{W}{e} r_{m,g} \frac{(\mu_{en}/\rho)_t}{(\mu_{en}/\rho)_m} \quad (4)$$

For measurements with an ionization chamber the reading obtained from the chamber, R, has to be related to the charge produced within the cavity at a reference temperature and pressure by the product of several correction factors, $\Pi\, k_R$

$$Q = R \Pi k_R \quad (5)$$

The factors contained in Πk_R include the electrometer calibration factor and correction factors for ion recombination, temperature and pressure, gas flow rate and leakage current. To apply equation (4) the mass of gas in the cavity has to be known. This can be obtained from the calibration factor of the tissue-equivalent chamber with photons ac which is defined as:

$$a_c = \frac{(D_{t^*})_c}{Q_c} \quad (6)$$

where subscript c refers to the photon calibration beam. If this is substituted into equation (4) we obtain:

$$m = \frac{1}{a_c}\frac{W_c}{e}\left(s_{m,g}\right)_c \left[\frac{(\mu_{en}/\rho)_t}{(\mu_{en}/\rho)_m}\right]_c \quad (7)$$

In this equation the gas-to-wall absorbed dose conversion factor, $r_{m,g}$ has been replaced by $(s_{m,g})_c$ since the chambers used for clinical neutron dosimetry are usually small enough to satisfy the conditions for the Bragg-Gray theory at the photon calibration energies normally used.

Absorbed dose in TE plastic adjacent to the cavity of the TE chamber can be calculated [Mijnheer and Williams, 1981] from the measured exposure, X_C:

$$(D_{TE^*})_C = X_C \frac{(W_{air})_C}{e}\left[\frac{(\mu_{en}/\rho)_{TE}}{(\mu_{en}/\rho)_{air}}\right]_c (\Pi k_A)_C \quad (8)$$

The correction factor $(\Pi k_A)_C$ accounts for the attenuation and scattering by the wall, central electrode and build-up cap of the chamber and also for the radiation scattered by the stem of the chamber into the sensitive part of the chamber. In addition, corrections should be made if there is any radial or axial non-uniformity in the field that is in the plane perpendicular to the central axis of the beam or along the central axis. The calibration factor with photons can now be written as:

$$a_C = \frac{X_C (f_t)_C (\Pi k_A)_C}{R_C (\Pi k_R)_C} = N_C (f_t)_C (\Pi k_A)_C \quad (9)$$

It should be noted that the product X_C $(f_t)_C$ $(\Pi k_A)_C$ does not represent the absorbed dose in tissue in the absence of the chamber but it represents the absorbed dose in tissue adjacent to the cavity of the chamber. N_C and N_k, are the exposure and air kerma calibration factors, defined as [Wojciech Bulski et al., 2008]:

$$N_C = \frac{X_C}{R_C (\Pi k_R)_C} \quad (10)$$

$$N_K = N_C \left(\frac{W_{air}}{e}\right)(1-g) \quad (11)$$

Where, g is the fraction of energy of secondary charged particles that is converted to Bremsstrahlung in air. The calculation of this fraction for electrons produced by ^{60}Co gamma rays in the graphite wall of an ionization chamber amounts to 0.003 [Boutillon and Perroche, 1985 and Kessler et al., 2010].

The aim of the work is to study the optimizing parameters affecting the sensitivity and stability of two tissue equivalent neutron ionization chambers types 33051 and 33053 in different types of γ- beams, for use as neutron secondary standard dosimeters in National Institute of Standards (NIS)- Egypt.

Also, to determine the correction factors required to eliminate perfectly the γ-component in neutron-gamma mixed fields. Finally, Comparing the obtained calibration factors with most ionization chambers commonly used internationally.

2. Experimental Work

Determination of the calibration factor with photons is usually made with an exposure standard chamber whose calibration is directly traceable to a national standards laboratory. The calibration should be made in air with the geometrical centre of the detectors being taken as the point of measurement [Oliver Ja¨kel 2009]. A build-up cap of the same material as the wall should be added if the wall thickness of the TE chamber wall is not sufficient to achieve charged-particle equilibrium. The chamber should be orientated so that its stem is perpendicular to the beam. [Broerse et al, 1981]

The measurements of air kerma and absorbed dose to water calibration factors for TE neutron ionization chambers are performed against the two NIS secondary standard dosimetry systems.

The calibration of TE neutron ionization chambers performed in two different reference gamma beams, ^{137}Cs, and ^{60}Co Gammatron therapy unit at NIS. The ^{137}Cs source used in this work type Gamma Beam-150B, manufactured by the Atomic Energy of Canada Limited. The present activity is 500 Ci, and dose rate is 1.235 Gy/h at 1 meter from the source center. The ^{60}Co therapeutic unit used in this work is Gammatron manufactured by Siemens, Germany. The present activity is 750 Ci, and dose rate about 5.94 Gy/h at one meter from the center of the source.

The X-ray machine used in this work is MCN-323 metal-ceramic Philips double pole x-ray tube. The MG325 Philips x-ray system is highly stabilized constant potential X-ray system. The H. V. and tube current adjustment range are from 15-320 kV and from 0 to 22.5 mA respectively. [Philips 1998].

The first NIS dosimetry system is Farmer electrometer type (NE-2570/1B) manufactured by Nuclear Enterprises Ltd. made in U.K. Farmer ionization chamber NE 2571 is a 0.6cc cylindrical manufactured by Nuclear Enterprise. This system used in this work in X-ray calibration.

The second dosimetry system used in calibration in both ^{60}Co and ^{137}Cs beams is the secondary standard NPL therapy level dosimetry system. The system is composed of an electrometer of type NE-2560. A 0.3 cm^3 ionization chamber type NE-2561. The system is made in U.K. manufactured by Nuclear Enterprises Ltd, Beenham. A laboratory timer of type NE-2546 with resolution 0.001 second is used for time measurements.

Two types of TE neutron ionization chambers TM33051 and TM33053, which are the thimble shape, are manufactured in Germany by PTW-FREIBURG. Figure (1) show a schematic diagram of two NIS TE neutron ionization chambers illustrating the internal construction and its dimension. For the evaluation of the attenuation in the chamber wall a set of different caps is applied. For chamber type 33051 the additional wall thickness are 1, 2, 3, 4, 6 and 8 mm A-150. Unidos electrometer type 10001 is manufactured by PTW-FREIBURG, Germany.

All chambers employed in neutron dosimetry are provided with gas inlet and outlet tubes. The gas system installation to provide the chamber with a steady, continuance and low gas flow rate consists of the items shown in Figure (2)

Two types of gases tissue substitutes were used, namely acetylene (C_2H_2) and carbon dioxide (CO_2). The two gases were supplied by El- Naser Company for Intermediate Chemicals Egypt. The C_2H_2 is a Technical Grade with purity 99.95 % supplied in specially designed steel cylinders with pressure 13 bar. The CO_2 is a Normal Grade with purity 99.995 % supplied in cylinder with high strength aluminum alloy with pressure 50 bar. The carbon percentage by mass in C_2H_2 and CO_2 are 92.3 and 27.3 respectively. The hydrogen percentage is 7.7 by mass in acetylene while the oxygen in CO_2 is 72.7 by mass. [ICRU, 1989]

The electrical air pump used to push air through neutron ionization chamber to refresh the cavity medium and study the difference between the static and air flow inside the cavity during measurements. The pump flow rate of air is in range from 30 to 1000 ml/min. It has two vents for air inlet & outlet and DC power supply 12 V, manufactured by Genitron Instruments GmbH, Heerstraße, Frankfort, Germany.

The IAEA standard dosimetric calibration phantom is Perspex cubic (30×30×30 cm^3) with Wall thickness 1.5 cm, water-filled container with open top and two entrance windows for horizontal beams. [ICRU, 1992].

Two types of calibrated thermometer were used during irradiation both in air and water. The first is high quality mercury-in-glass thermometers in the range from 19 to 35 ^{o}C a precision of 0.1 ^{o}C. The second is a digital thermometer measuring in the range from -10 to 80 °C with a precision of 0.1 ^{o}C designed and developed by TFA Germany.

A calibrated digital manometer was used for air pressure measurement; it covers range up to 60 in Hg or 2031.8 mbar. It is a Meriam Instrument, manufactured by a Scott Fetzer Company.

The correction factors, Πk_R for Temperature and Pressure($k_{t,p}$), Electrometer (k_e), Ion

Recombination (k_s), Current leakage (k_l), Polarity Effect (k_p), Gas Flow Rate Effect (k_f) and Humidity (k_h), which convert the reading, *R*, taken from the chamber, to the charge, *Q*, produced within an ideal cavity at reference conditions.

Πk_A contains all the correction factors that are valid during measurements in air as well as in the water phantom. Πk_A is a composite factor and equal to the product of the factors Wall and build-up cap (kw), stem effect (k_{st}), Radial non Uniformity (k_{rn}) and Axial non Uniformity (k_{an}). [Niatel et al, 1975]

3. Calibration Methods:

Calibration of TE Neutron Chamber in ^{137}Cs and ^{60}Co Beams :

In-air dosimetry was performed at the conditions where source to chamber distance (SCD) =100 cm with field size equal to 10×10 cm^2 at the position of the chamber. The center of the sensitive volume of the ion chamber was aligned by means of laser beam to the center of the radiation field [Yanxiao Huang et al., 2010]. The ion chamber was oriented with the chamber type and serial number inscribed on the stem facing the source and the build-up cap was used for in-air dosimetry in order to avoid measuring in the buildup region. The air kerma calibration factor to be recorded is calculated by:

$$N_K = K_{air} / M_{Cs} \qquad (12)$$

where K_{air} is the air kerma determined by the standard and M_{Cs} is the charge or reading from the chamber to be calibrated, corrected for the reference values of 20°C and 101.325 kPa of ambient temperature and air pressure [Arbabi et al., 2010].

In-water dosimetry was performed as the conditions recommended by IAEA [IAEA, 2000].The ion chamber axis was perpendicular to the central axis of the beam; the chamber was oriented so that the chamber type and serial number inscribed on the stem facing the source. In-water measurements were performed without the build-up cap because the ion chamber was inserted inside a waterproof sleeve.

The absorbed dose to water calibration factor $N_{D,w}$ for the chamber to be calibrated is calculated from the equation:

$$N_{Dw} = D_w / M_{Cs,f} \qquad (13)$$

Where D_w is the absorbed dose to water derived from measurements by the standard and $M_{Cs,f}$ is the charge or reading of the chamber to be calibrated, corrected for the reference conditions of temperature and air pressure [Zhe Chen et al., 2007].

X-Ray Calibration of TE Neutron Chamber & Farmer Dosimetry System

The quality assurance measurements for the X-ray generator system was carried out using x-ray test device Model 4000M+ manufactured by Victoreen. These quality assurance measurements were routinely performed for testing the applied kV on the tube. It was found that, the applied kV on the tube was constant during all measurements within the uncertainty limit according to manufacture specification of the X-ray generator.

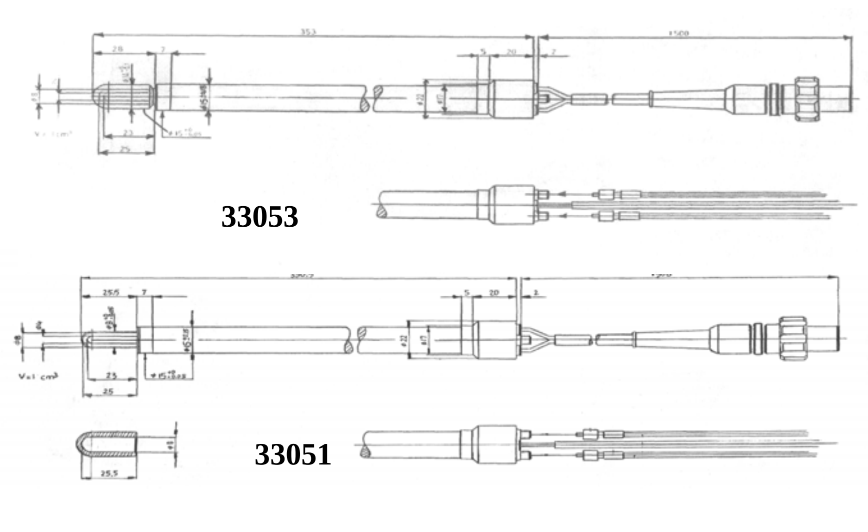

Figure (1): Schematic diagram of two NIS TE neutron ionization chambers

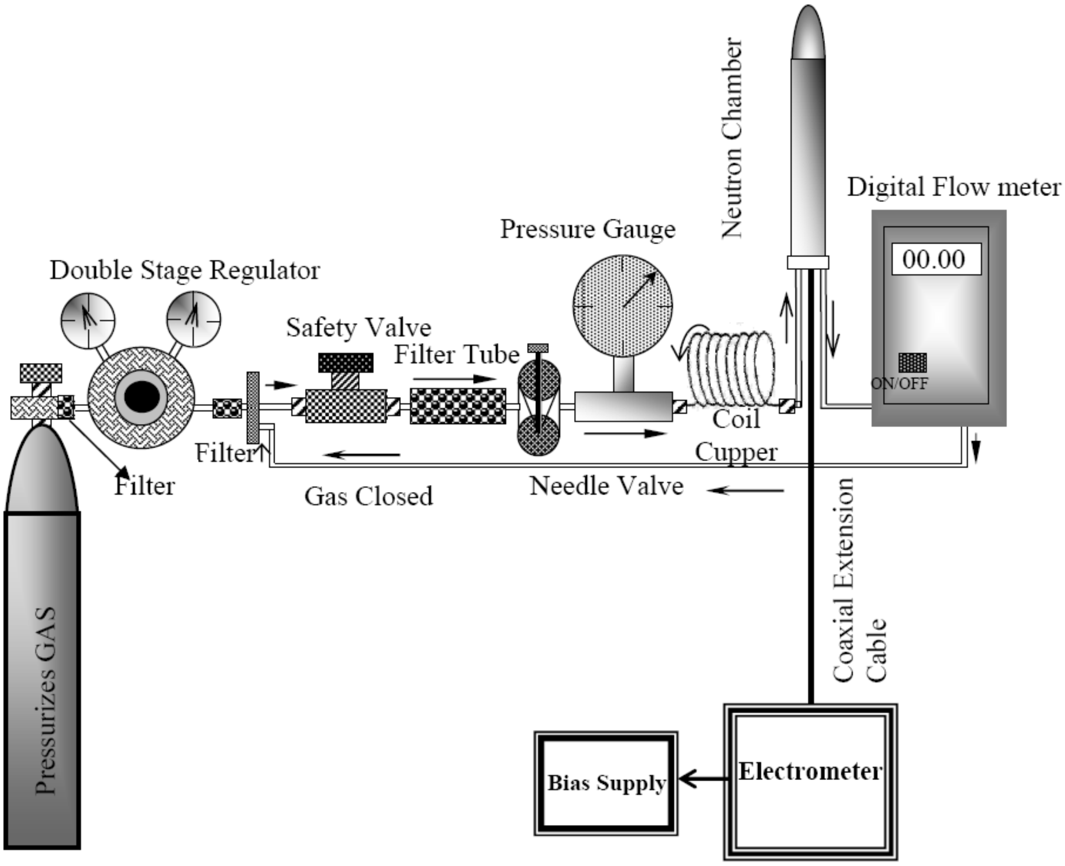

Figure (2): Shows a schematic diagram for developed gas system connected to tissue equivalent neutron ionization chamber.

4. Results and Discussion:

4.1 Warm-up

The warm-up time for each chamber was studied and about 30 min warm-up was found to be necessary to give stable and reproducible data. Warming up to 1 hour is desired to reduce the uncertainty values.

4.2 Polarity Correction Factor

Polarity correction factor was measured when the chambers were filled with air or flushed with CO_2 and C_2H_2 in cesium beam whereas it was measured when the chambers were filled with air only in cobalt beam. Polarity correction factor values for the two neutron chambers using different sources and gases are given in Table (I). It is clear from the table that the values of the polarity correction factor when the chambers were filled with air less than 1.0025, which are acceptable [IAEA, 1994]. However, when the chambers were flushed with CO_2 or C_2H_2, the polarity correction factor values in the range 1.0038 % to 1.00421 % for the two chambers used.

4.3 Stem Scattering Correction Factor

Stem scattering correction factor for the two neutron chambers are given in Table (II). The stem effect values of the two neutron chamber [33051 (Al stem) and 33053 (Acrylic stem)] in ^{60}Co beam are slightly higher than that in ^{137}Cs beam and with lower percentage standard deviation. This may be due to the different stem material of two chambers.

4.4 Ion Recombination Correction Factor

The calculated values of ion recombination correction factor are represented in Table (III). It is clear from the table that the two chambers show slight dependence of the ion recombination factor on the type of the filling gas (air, C_2H_2 and CO_2) and the energy of the gamma rays.

Table (I): The polarity correction factor for the two neutron ionization chambers in different gamma sources and its percentage standard deviation.

Source type	Chamber type	Polarity correction factor &Gas type			%σ		
		Air	CO_2	C_2H_2	Air	CO_2	C_2H_2
^{60}Co	33051	1.0011			0.007		
	33053	1.00177			0.043		
^{137}Cs	33051	1.0019	1.00384	1.0038	0.014	0.028	0.047
	33053	1.00244	1.00421	1.00409	0.010	0.028	0.037

Table (II): Stem scattering correction factor and its percentage standard deviation.

Source type	Chamber type	Stem scattering correction factor	%σ
^{60}Co	33051	0.9993	0.015
	33053	0.9991	0.008
^{137}Cs	33051	0.9982	0.050
	33053	0.9961	0.020

Table (III): Ion recombination correction factor in different gamma sources and its percentage standard deviation.

Source type	Chamber type	Ion recombination correction factor			%σ		
		Air	C_2H_2	CO_2	Air	C_2H_2	CO_2
^{60}Co	33051	1.004	1.005	1.022	0.01	0.006	0.001
	33053	1.001	1.002	1.004	0.02	0.011	0.004
^{137}Cs	33051	1.032	1.001	1.028	0.01	0.024	0.015
	33053	1.015	1.001	1.004	0.006	0.12	0.007

Table (IV): The leakage current correction factor (k_l) for two neutron ionization chambers filled with different gases in ^{60}Co and ^{137}Cs beams.

Source type	Chamber type	Leakage current correction factor		
		Air	C_2H_2	CO_2
^{60}Co	33051	1.0002		
	33053	1.0001		
^{137}Cs	33051	1.0005	1.0007	1.0004
	33053	1.0003	1.0003	1.0004

4.5 Leakage Current Correction Factor

Leakage current correction factor was measured when the chambers were filled with air or flushed with CO_2 and C_2H_2 in ^{137}Cs beam whereas it was measured when the chambers were filled with air only in ^{60}Co beam.

The leakage current is divided into two categories, pre-irradiation and post-irradiation leakage. The measured pre-irradiation leakage values of the ionization current produced by minimum air kerma are shown in Table (IV). The results indicate that the percentage pre-irradiation leakage current values below the maximum permissible range (up to 0.5%), IAEA, 1994. The post-irradiation current leakage value was nearly zero because the field size was 10×10 cm^2, that permits no full stem irradiation and all chambers used with guarded stems that permits no leakage.

4.6 Wall Thickness and Build up Cap Correction Factors

The neutron chamber 33051 was used to study the effect of wall thickness and build up cap because it is the only chamber which has the possibility of varying the cavity wall thicknesses with the same material of original wall cavity.

Figure (3a) shows the variation of the relative charge as a function of cavity wall thicknesses for ^{60}Co beam when the chamber was filled with air. It is clear from the figure that there is high dependence of the measured relative charge on cavity wall thickness till 3 mm which is equivalents to about 338 mg/cm^2 in unit mass density. At higher cavity wall thickness the dependence slightly decreased with linear negative slope as shown in Figure (63b). The extrapolation of the linear part of the attenuation curve to zero thickness was found to be at 1.111 ± 0.0002, which is considered as the correction factor k_w.

Figure (4) shows the variation of the relative charge as a function of cavity wall thicknesses for ^{137}Cs beam when the chamber was filled with air and CO_2 gas flow. The results indicate strong negative dependence of the relative charge on the cavity thicknesses till 2 mm (225 mg/cm^2) and 3 mm when the chamber was filled with air and CO_2 gas flow respectively. At higher cavity thickness the charge dependence on the thickness was lower. The extrapolation of the linear dependence of the relative charge on the cavity wall thicknesses to zero value, the values of kw were found to be at 1.004 ± 0.0011 and 1.009 ± 0.0020 for the chamber filled with air and CO_2 gas flow respectively, as shown in Figures (5a) and (5b).

The results showed that the increase of wall thickness increased the sensitivity of the chamber to gamma radiation till a wall thickness of 3mm. High thickness did not show any more increase of the ionic current. This result indicates that the ions are emitted from the walls of the chamber resulting from the interaction with the gamma rays. At thickness higher than 3 mm self absorption of the emitted ions from the walls occur which prevents no more ions of reaching the chamber cavity.

4.7 Gas System Calibration

Plotting a curve of gas system, representing the relation between the pressure in m bar inside the cavity of neutron chamber and the flow rate in ml/min. The result indicate linear dependence of gas flow on the pressure with correlation coefficient R = 0.9999 and the correction factor is 3.14 ± 0.26. The slope of the line is 3.12 ± 0.006.

4.8 Gas Flow-Rate Correction Factor

Figure (6a) shows the effect of gas flow rate on the charge of neutron chamber 33051 flushed with C_2H_2 gas flow, relative to the charge when the chamber was filled with atmospheric air for ^{241}Am-Be, ^{60}Co and ^{137}Cs after a preflush with 100 cm^3 C_2H_2.

It is clear from the figure that up to 1 ml/min, the increase in the sensitivity is proportional to the gas flow rate for all used radiation sources. In the region from 10 ml/min up to 12.5 ml/min slight dependence of the relative ionization chamber reading on gas flow rate. By increasing the gas flow rate up to about 13 ml/min the charge of the chamber remains rather constant. It can be seen that in the gas flow rate region from 13 ml/min to 31 ml/min the sensitivity of the ionization chamber can be increased by about 10 %, 8 % and 3 % for ^{241}Am-Be, ^{60}Co and ^{137}Cs respectively.

Figure (6b) shows the effect of gas flow rate on the relative charge (gas/airatoms) of neutron chamber 33051 flushed with CO_2 gas flow, for ^{241}Am-Be, ^{60}Co and ^{137}Cs. The region from 12.5 ml/min to 31 ml/min the relative charge of chamber was more stable with increasing the gas flow rate. From the figure, it is clear that C_2H_2 gas gave higher sensitivity to detect neutrons than CO_2 and air. This result shows the role of recoil protons in the C_2H_2 gas by fast neutrons. Moreover, the advantage of the use of C_2H_2 as filling gas in the neutron chambers is that it decreases the sensitivity of the chamber to detect gamma rays and increase its sensitivity for neutron detection, which is considered as one of the main objective of the present work.

Figure (7) shows the relation between relative charge (gas/airatoms) and the gas flow rate for neutron chamber 33051 in ^{241}Am-Be neutron beam when the chamber was flushed with C_2H_2, CO_2 and

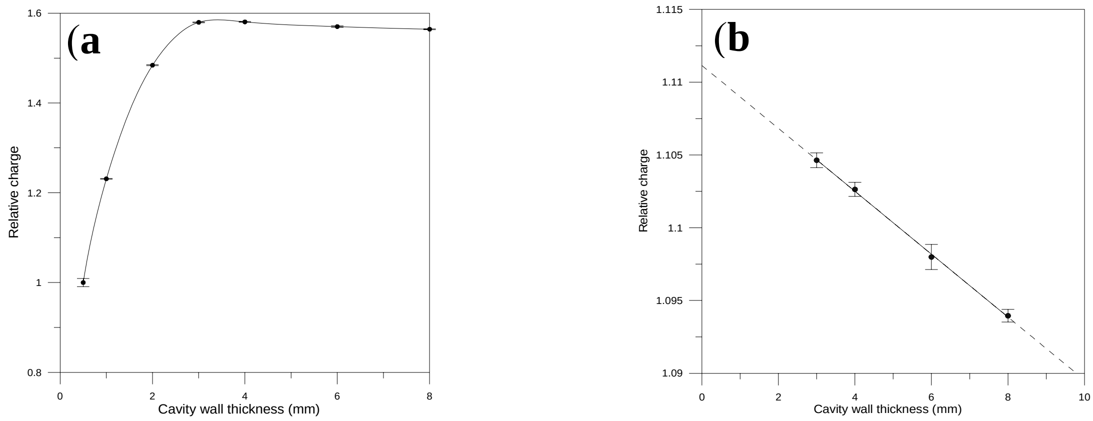

Figure (3): The relation between the relative charge and the cavity wall thickness for chamber 33051 filled with atmospheric air at ^{60}Co source (a) all thickness and (b) the extrapolation of the linear part.

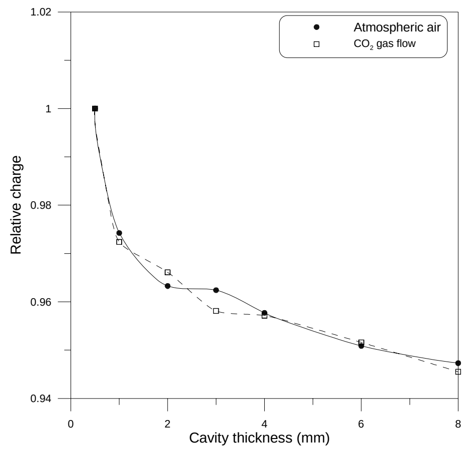

Figure (4): The effect of cavity thickness on the reading of the neutron ionization chamber 33051 in case of CO_2 gas flow and atmospheric air from ^{137}Cs source.

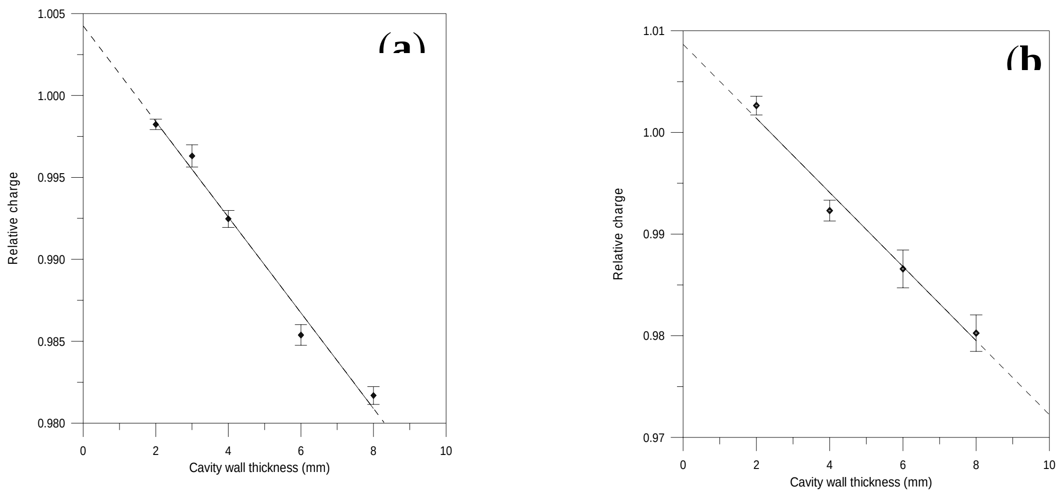

Figure (5): The relation between the relative charge and the cavity wall thickness for chamber 33051 at ^{137}Cs source filled with (a) atmospheric air and (b) CO_2 gas.

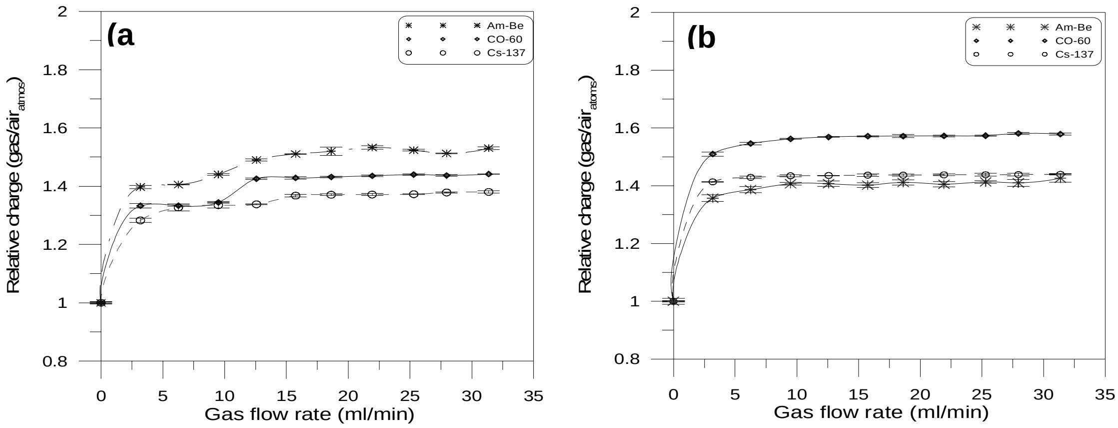

Figure (6): Represents the relation between relative charge and gas flow rate (ml/min) for neutron chamber 33051 filled with (a) C_2H_2 and (b) CO_2.

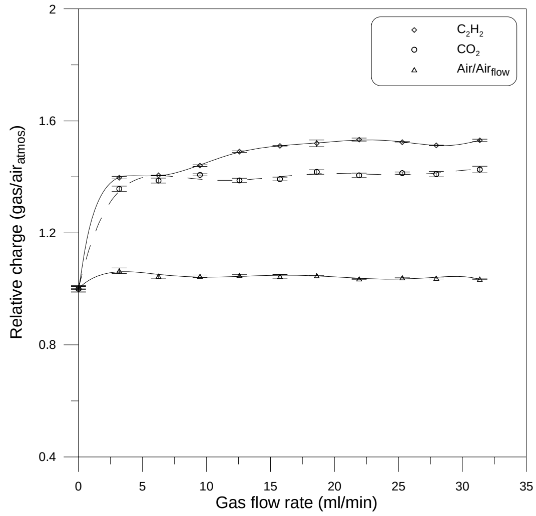

Figure (7): Represents the relation between relative charge and gas flow rate (ml/min) for neutron chamber 33051 using ^{241}Am-Be neutron source.

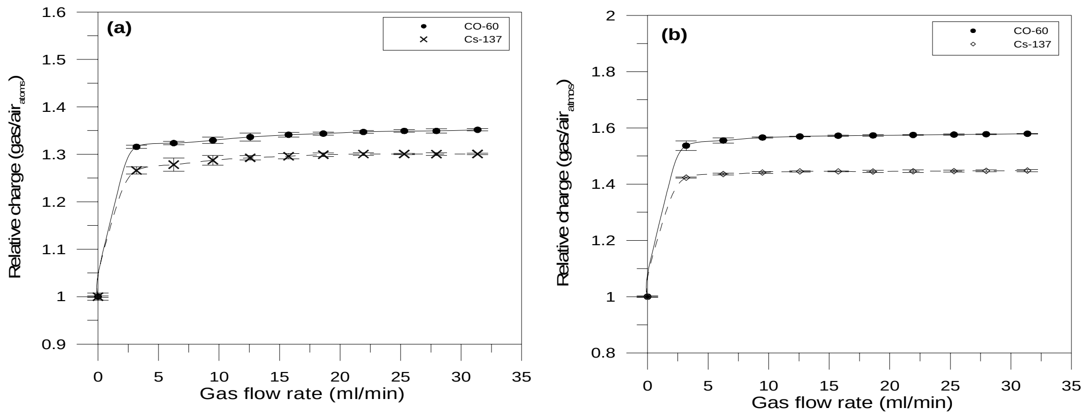

Figure (8): Represents the relation between relative charge and gas flow rate (ml/min) for neutron chamber 33053 filled with (a) C_2H_2 and (b) CO_2.

air. It is clear from the figure that the maximum sensitivity of the neutron chamber 33051 for C_2H_2 gas whereas the minimum sensitivity for air/airflow. Up to 13 ml/min the sensitivity of the neutron chamber 33051 can be increased by about 10 %, 7 % and 4 % for C_2H_2, CO_2 and air/airflow respectively. The ratio of the relative charge for chamber 33051 filled with atmospheric air to air flow rate is about 1.05 which is assumed to be only one. This finding may be due to the recombination reactions between O_2 and N_2 molecules forming atmospheric air which are kept in static form under strong electric field strength of 400 kV/m (applied voltage to the chamber is 400 V and the distance between the internal chamber electrodes is 4 mm). Nitric oxides may be generated within atmospheric air filling the chamber in static form condition under the influence of this strong electric field. These additional growing impurities in the filling air may be a reason for this increase of the chamber reading.

Figures (8 a and b) show the effect of gas flow rate on the relative charge (gas/airatoms) of neutron chamber 33053 using different gases (C_2H_2 and CO_2) and ^{60}Co and ^{137}Cs sources. Comparing these figures with Figures (6 a and b), it can be seen that the two chambers have the same sensitivity when they were flushed with CO_2 for two gamma sources. When the chambers were flushed with C_2H_2 gas, the sensitivity of neutron chamber 33051 is greater than the chamber 33053 with 38 % in the ^{60}Co beam. In the ^{137}Cs beam the sensitivity of the neutron chamber 33051 is less than the chamber 33053 with 2.8 %. Table (V) shows the values of gas flow rate for two neutron ionization chamber with different gamma sources and the percentage of standard deviation.

4.9.1 Radial Uniformity Correction Factor

Figures (9 a and b) represent the radial beam non-uniformity over the cavity thickness in air for 33051 neutron ionization chamber flushed with CO_2 gas and for 33053 neutron chamber flushed with C_2H_2 gas flow using ^{137}Cs gamma beam. From the two figures it is clear that the cesium beam is symmetrical over the studied range. The deviation from the central field point (0,0) to the point ±12 cm is about 1.6 % for 33051 chamber and to the point ± 9 cm is about 1.2 % for 33053 neutron chamber. Beam uniformity is much more homogeneous at the field center.

4.9.2 Axial Uniformity Correction Factor

Figures (10 a and b) represent the axial beam non-uniformity over the cavity thickness in air for 33051 neutron ionization chamber flushed with CO_2 gas and for 33053 neutron chamber flushed with C_2H_2 gas using ^{137}Cs gamma beam. From the two figures it is clear that the radiation beam is symmetrical over the studied range (±10 cm) in the case of chamber 33051, the deviation from the central field point (0,0) is about 4.24% upward and 4.97 % downward. The studied range in the case of chamber 33053 is (±15 cm), The maximum deviation from the central field point (0,0) is about 4.80 % upward and 5.55 % downward direction. Beam uniformity is noticeable at the field center.

Figures (11) and (12) represent the radiation contour pattern and wire frame mapping for both radial and axial uniformity for the two neutron ionization chambers 33051 and 33053 filled with air in cobalt beam. From the figures it is clear that the radiation beam is not symmetrical over the studied range (±5 cm). For the chamber 33051 filled with air, the deviation from the (0,0) point to the point ±5 cm for the radial direction was 2.7 % and 4.5 %, for axial direction was 3.2 % and 8.5 % for upward and downward direction.

For chamber 33053 the deviation from the (0,0) point to the point ± 5 cm for radial direction was 1.6 % and 2.7 %, for axial direction was 2 % and 6.6 % for upward and downward direction. Beam uniformity is remarkable at the field center. Table (VI) shows the values of Radial & Axial beam uniformity correction factor for two neutron ionization chambers.

4.10 Resultant Calibration of TE Neutron Ionization chambers

Table (VII) shows the results of whole calibration coefficients in air in terms of air kerma (N_k) with unit mGy/nC in different radiation quality. Table (VIII) shows the calibration coefficients in water phantom in terms of absorbed dose to water (N_{Dw}) with unit mGy/nC experimentally and calculated using ^{137}Cs and ^{60}Co, experimental ratio N_{Dw}/N_k in cesium beam for neutron ionization chambers.

The experimental ratio N_{Dw}/N_k for a given neutron chambers give useful information about their uniformity. The usual situation for chambers calibrated only in air having air kerma factor (N_k), the absorbed dose to water factor (N_{Dw}) can be calculated using this ratio which based on a code of practice used. From Table (VII), it is clear that the values of air kerma (N_k) for both neutron chambers types 33051 and 33053 are energy and gas filling dependents.

Figures (13 a and b) illustrate the relation between the relative air kerma N_k normalized to cobalt beam and energies for different radiation quality for two NIS secondary standard ionization chambers (NPL and Farmer) and two neutron ionization chambers 33053 and 33051 with different gases. It is clear that the results of NPL and Farmer ionization chambers are nearly coincidence and energy independent. The neutron chambers with different gases are not compatible at low X-ray energies while more consistency at higher energies, it is emphasized that energy dependent.

Table (V): The values of gas flow rate correction factor for the two neutron ionization chambers in ^{60}Co and ^{137}Cs beams.

Source type	Chamber type	Flow rate correction factor & Gas type			%σ		
		Air	C_2H_2	CO_2	Air	C_2H_2	CO_2
^{60}Co	33051	0.98154	0.99903	0.99993	0.02	0.070	0.007
	33053	0.99849	0.99928	0.99973	0.01	0.030	0.020
^{137}Cs	33051		0.99991	0.99997		0.030	0.010
	33053		0.99941	1.00000		0.024	0.002

Table (VI): The values of Radial & Axial beam uniformity correction factors for two neutron ionization chambers.

Source type	Chamber type	Radial beam uniformity correction factor & Gas type			Axial beam uniformity correction factor & Gas type		
		Air	C_2H_2	CO_2	Air	C_2H_2	CO_2
^{60}Co	33051	1.004			0.996		
	33053	0.997			1.006		
^{137}Cs	33051			1.000			0.999
	33053		0.9997			1.004	

Table (VII): shows the calibration coefficients in terms of air kerma in X-ray beam, ^{137}Cs and ^{60}Co for neutron ionization chambers.

Radiation quality		N_k, Neutron chamber type 33051			N_k, Neutron chamber type 33053		
		Air static	C_2H_2	CO_2	Air static	C_2H_2	CO_2
		mGy/nC			mGy/nC		
X-Ray	100 kV	40.38	34.03	26.11	35.97	30.30	23.24
	180 kV	35.45	28.72	23.09	32.04	25.82	20.74
	250 kV	33.75	26.34	22.23	30.82	24.01	20.25
^{137}Cs		31.11	22.89	19.65	28.33	22.02	18.85
^{60}Co		30.29	21.24	19.32	28.24	21.00	18.02

Table (VIII): shows the calibration coefficients in terms of absorbed dose to water in ^{137}Cs and ^{60}Co, experimental ratio N_{Dw}/N_k in ^{137}Cs beam for neutron ionization chambers.

Radiation quality	Type of determination	Neutron chamber type 33051			Neutron chamber type 33053		
		N_{Dw}, Air static	N_{Dw}, C_2H_2	N_{Dw}, CO_2	N_{Dw}, Air static	N_{Dw}, C_2H_2	N_{Dw}, CO_2
		mGy/nC			mGy/nC		
^{137}Cs	Experimentally	35.85	27.52	24.74	35.13	27.42	24.42
	N_{Dw}/N_k	1.153	1.202	1.259	1.240	1.245	1.296

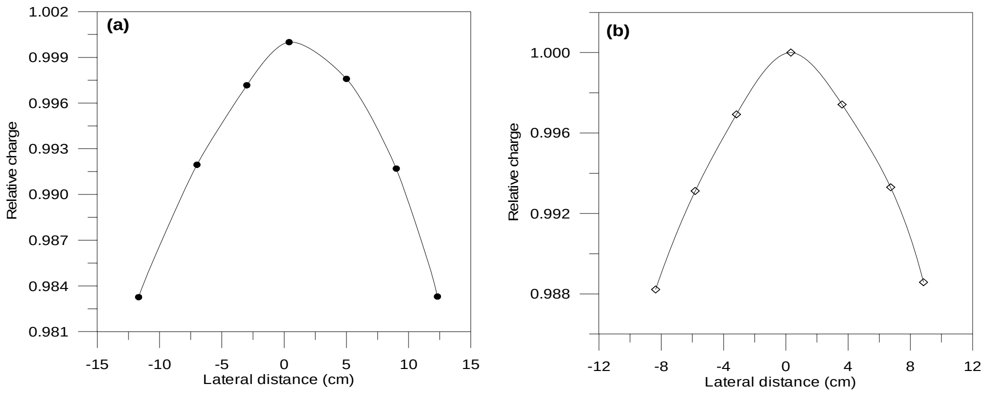

Figure (9): Shows the relation between the relative charge and lateral distance (cm) for neutron chamber at ^{137}Cs source filled with (a) 33051 CO_2 (b) 33053 C_2H_2

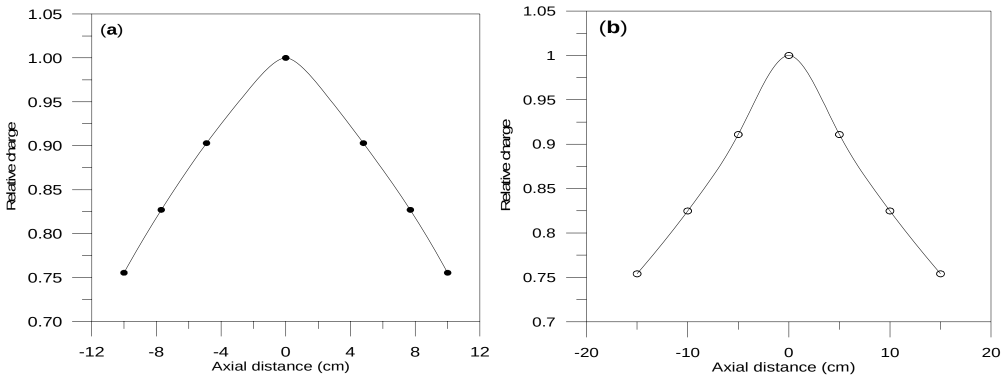

Figure (10): Shows the relation between the relative charge and the axial distance (cm) for neutron chamber from ^{137}Cs source filled with (a) 33051 CO_2 (b) 33053 C_2H_2

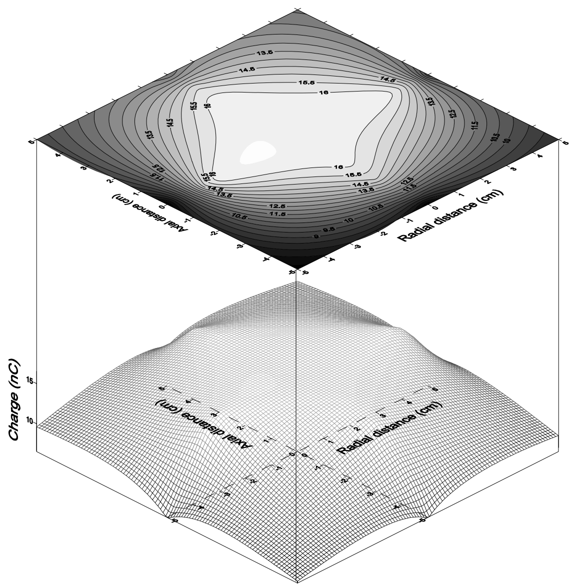

Figure (11): Shows the relation between the charge and both radial and axial distance (cm) from the source center for neutron chamber 33051 with atmospheric air from ^{60}Co source.

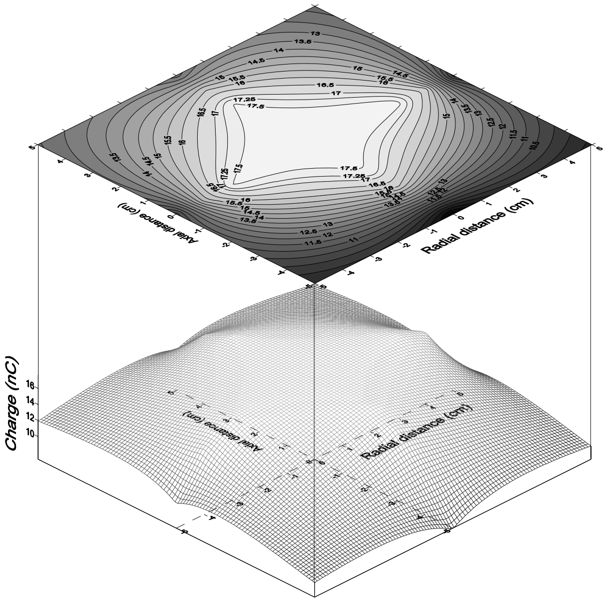

Figure (12): Shows the relation between the charge and both radial and axial distance (cm) from the source center for neutron chamber 33053 with atmospheric air from ^{60}Co source.

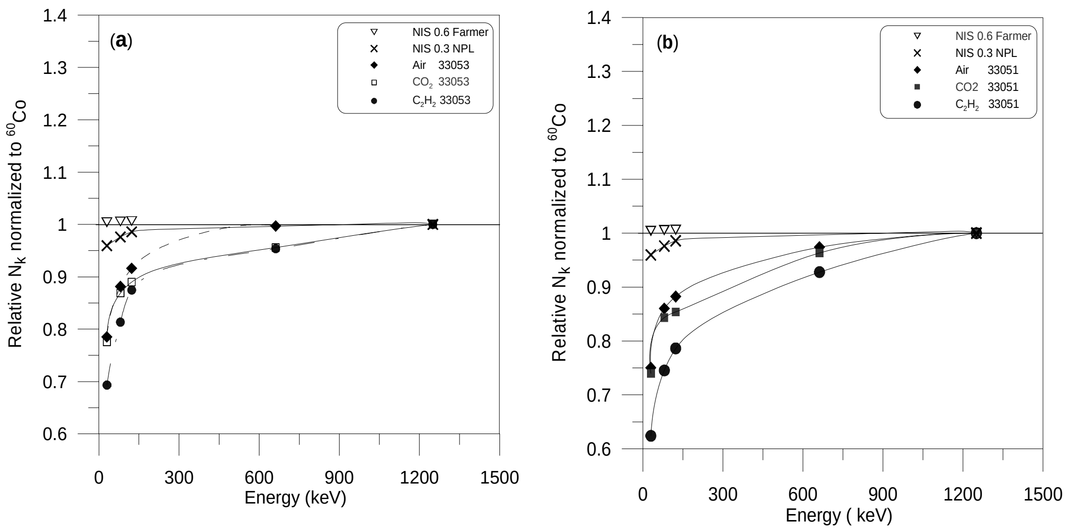

Figure (13): Represents the relation between the relative air kerma (N_k) normalized to ^{60}Co and radiation energies for secondary standard 0.6 cm^3 farmer and 0.3 cm^3 NPL chambers and neutron chamber filled with different gases (a) 33053 and (b) 33051.

4.11 The Sensitivity of Neutron Chamber Compared to Gamma Chamber

Figures (13 a and b) show the relation between collected charge and source -to-detector distance for neutron chamber 33051 compared with the secondary standard gamma ionization chamber (NPL chamber) normalized to its volume in ^{60}Co and ^{137}Cs beams.

The correction factors were 1.085 and 1.098, respectively for ^{60}Co and ^{137}Cs, for neutron chamber filled with atmospheric air. However, when the neutron chamber was flushed with C_2H_2 or CO_2, the response was increased. The correction factors were 0.743 and 0.679, respectively in ^{60}Co beam, in ^{137}Cs beam they were 0.809 and 0.694, respectively.

Figures (14 a and b) show the relation between collected charge and source -to-detector distance for neutron chamber 33053. The correction factors were 0.996 and 1.049 for cobalt and cesium, respectively for neutron chamber filled with atmospheric air. However, when the neutron chamber 33053 was flushed with C_2H_2 or CO_2, the correction factors were 0.735 and 0.633 respectively in ^{60}Co beam, whereas they were 0.774 and 0.666, respectively in ^{137}Cs beam.

5. Conclusion

The sensitivity of the TE neutron ionization chamber to γ-beams must be studied and all the discussed correction factors are implemented to determine the photon calibration factors.

The warm-up time for each chamber was studied and about 30 min warm-up was found to be necessary to give stable and reproducible data. Filling the chambers with C_2H_2 commercial gas gave more stable readings while atmospheric air and CO_2 gas showed fluctuations during the warming-up period demonstrated (160 min).

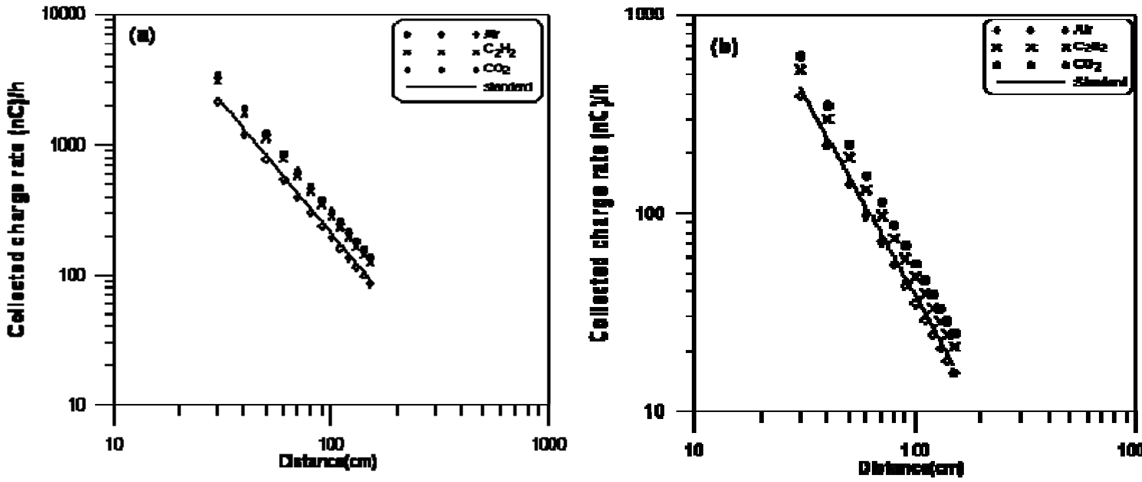

Figure (14): Shows the sensitivity of neutron chamber 33051 with different gas compared with secondary standard gamma ionization chamber in (a) cobalt beam (b) cesium beam.

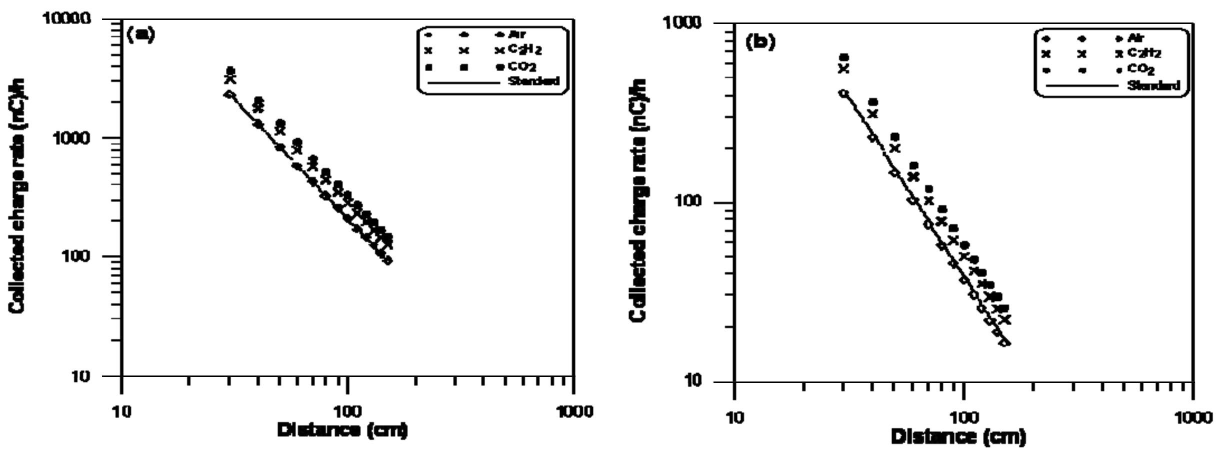

Figure (15): Shows the sensitivity of neutron chamber 33053 with different gases compared with secondary standard gamma ionization chamber in (a) cobalt beam (b) cesium beam.

The results showed that the increase of wall thickness increased the sensitivity of the chamber to gamma radiation till a wall thickness of 3mm. High thickness did not show any more increase of the ionic current. This result indicates that the ions are emitted from the walls of the chamber resulting from the interaction with the gamma rays. At thickness higher than 3 mm self absorption of the emitted ions from the walls occur which prevents no more ions of reaching the chamber cavity. The neutron ionization chambers filled with C_2H_2 gas flow of 18.6 ml/min (as a tissue equivalent gas) can be used as a secondary standard for measuring neutron equivalent dose rates. It has the advantage of increasing the sensitivity of the chamber to detect fast neutrons and decreasing its sensitivity for gamma rays.

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